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Online condition monitoring of IGBT modules using voltage change rate identification

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ABSTRACT

As insulated gate bipolar transistors (IGBTs) have gained an important status in a wide range of applications, reliability, and availability of these units are of paramount importance to meet stringent requirements spelled in aviation and industrial standards. Reliability of a power converter is mainly verbalized by the failure rate of power modules. Hence, monitoring IGBTs degradation is very crucial to give early sign of power-module-related failures in power converters. This paper proposes a new potential precursor parameter for IGBTs based on voltage change rate to detect early failure of power modules. The proposed method pays more attention to power modules with chip solder fatigue and bond-wire lift off as a major failure mechanism. An experimental setup using an accelerated power cycling machine is constructed to trigger degradations and failures on several IGBT modules. The experimental results indicate that voltage change rates of the IGBT modules decrease with ageing over time. It is found that the local damage induced by ageing over time changes the parasitic capacitances of an IGBT that leads to a decrease of the voltage change rate of the device.

1. Introduction

Reliability of a power converter in a mission-critical system is very importance in which each component in the power converters affects the system reliability and robustness. Throughout the power converter lifetime, power converter components such as power modules and capacitors experience complete failures due to electrical and thermal stresses caused by dynamic load conditions, system transients, and environmental conditions. According to two surveys, power semiconductor devices account for 21% and 34% of total failure distribution in power converter systems [1,2]. Due to continuous enhancement, the failure rate of power electronics devices has dropped from 1000 FIT (“1FIT” is equal to 1 failure per 10^9 device hours or failure per one billion hours) in the year 1995, to 20 FIT in the year 2000 [3], and it has further dropped to few FITs in recent years [4]. Irrespective of the wide effort to increase the lifetime of power semiconductor devices, failure of power devices have been witnessed continuously [5–7].

Most of power electronic converters use insulated gate bipolar transistors (IGBTs) as switching devices for various applications in the power range from few hundred watts to several megawatts. Many efforts have been dedicated to minimize the IGBTs wear-out failures such as solder-die degradation and bond-wire lift-off failure. These failures are due to differences in CTEs (coefficient of thermal expansions) in the material interfaces caused by power cycling or thermal cycling.

One promising solution to address this issue is to perform condition monitoring for an early diagnosis of potential wear-out failures and implement lifetime estimation technique of power devices through suitable prognostic methodologies. Several studies have been reported earlier for identification of IGBTs wear-out failures using their electrical parameters such as forward voltage, saturation voltage ($V_{ce\text{-}sat}$), gate-threshold voltage ($V_{ge,th}$), gate-emitter current (I_{ges}), short circuit current (I_{sc}), thermal impedance ($R_{thj\text{-}c}$), turn-on and turn-off switching times [8–10]. IGBT forward voltage (Vce,on) has been proposed as a precursor parameter to identify the bond-wire lift-off failure [11]. However, it was reported in that 5% increase of $V_{ce,on}$ indicate the bond-wire damage. Considering real-time measurement error, the 5% change may go un-noticeable. Therefore, methods using IGBT's forward voltage may not be suitable for real-time condition monitoring applications. Another commonly used method to detect solder-die degradation failure is thermal resistance monitoring. However, this method required accurate estimation of junction temperature. Monitoring of gate-emitter current (I_{ges}), gate-threshold ($V_{ge,th}$), turn-on and turn-off times can be useful to identify the IGBT chip failure detect. However, these parameters require a complex measurement circuit. Moreover, detecting ageing of power semiconductor device is more challenging because most of the existing techniques are unable to identify failure

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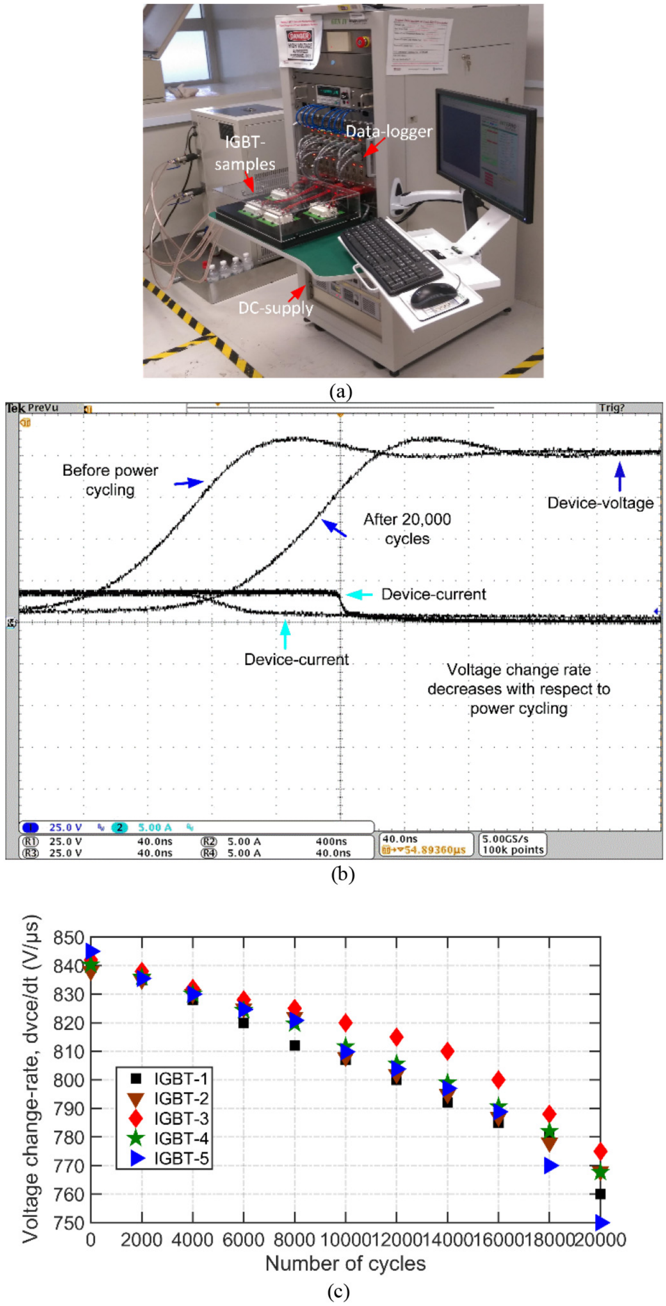

(a)

(b)

(c)

Fig. 1. (a) Accelerated ageing test-setup.
(b) Voltage change rate $\left(\frac{dv_{cE}}{dt}\right)$ variation during power cycling (IGBT-1); i_c 5[A/div], V_{CE} 25[V/div] and time, t 40[ns/div].
(c) Plotted voltage change rate $\left(\frac{dv_{cE}}{dt}\right)$ variation due to power cycling for the rest of the samples;

mechanism at an incipient stage.

This paper examines the voltage change rate (dv_{ce}/dt) of an IGBT as a critical precursor parameter to detect early degradation of power modules. The details of accelerated ageing and the concurrent measurement of precursor parameter of IGBT amid the degradation process are experimentally studied. In addition, this paper presents the influence of ageing in the parasitic capacitances (gate-collector capacitance) and its relation to the proposed precursor parameter. Finally, a PSPICE simulation model has been developed to study the relation between the voltage change rate and the permanent changes in the gate-collector capacitance of an IGBT device.

2. Accelerated ageing

Accelerated ageing test methodologies are essential to induce components failure and degradation into power electronics systems. In general, accelerated ageing tests are used to perform material degradation, and to examine the influence of thermal stress on the material interfaces in power modules. It has been reported that thermal mismatch in the material interfaces will cause wear-out failures [11–13]. Fig. 1(a) shows an experimental setup for accelerated ageing of power devices used in the following discussion. The developed experimental setup allows us to perform thermal cycling tests with constant "dc" current injection or pulse width modulation (PWM) current injection with the desired temperature during the thermal cycling period. Although many thermal cycling tests performed on IGBT devices use DC current injection method [14], this paper uses PWM current injection to degrade power modules because, it has been reported that [14], this constant "dc" current approach fails to emulate realistic operating conditions.

This paper uses five Non-Punch through IGBT devices (SKM150GB12T4G) from Semikron to examine the degradation of power modules. All the power modules used in the experiments are from the same production batch. The degradation is achieved by applying 100-V and 200-A PWM current injection, and controlling the minimum and maximum temperature of power modules to 70 °C and 125 °C, respectively, by using a liquid cooling. The temperatures of the power modules are estimated by measuring device forward voltages ($V_{ce,on}$) as a temperature sensitive electrical parameter. For every 2000 temperature cycles, the voltage change rates was obtained using an oscilloscope under ambient temperature conditions (25 °C) with applied DC link voltage of 100 V. This ageing test has been continued for twenty thousand temperature cycles. Fig. 1(b) shows the voltage change rate $\left(\frac{dv_{cE}}{dt}\right)$ of an IGBT sample-1, captured before and after power cycling experiment. From the result, it is proven that the ageing leads to changes in the voltage change rate, and it has been observed that voltage change rate decreased almost 10% from the initial value.

Fig. 1(c) shows the variation of voltage change rates $\left(\frac{dv_{cE}}{dt}\right)$ for the rest of the IGBT samples. As seen, there is small differences in voltage change rate measurements, and this may be due to intrinsic variations in the fabrication process such as channel length and doping. Nevertheless, investigation results from the IGBT samples conclude that degradation of power modules has been reflected in the voltage change rate parameter, and the maximum decrease was 12% observed at IGBT-5. Therefore, from the experiment it is evident that the IGBT voltage change rate captures the degradation process in such a way that it could be an early indication to identify the ageing as well as wear-out failures in the IGBT modules.

3. Experimental verification

One of the problems associated with the electrical precursor parameters of power semiconductor devices, including the proposed voltage change rate, is their dependency on the ageing as well as the current operating conditions, more importantly, junction temperature, and it is confirmed by the Bryan et al. [15], where they investigated IGBT voltage change rate as a temperature sensitive parameter to estimate the junction temperature of power modules.

Therefore, to alleviate these difficulties, the measured voltage change rate is normalized based on operating conditions including the device junction temperature before used as a precursor parameter to identify the wear-out failures. Moreover, the voltage change rate measurement requires high voltage and high bandwidth sensors which prove to be expensive. Therefore, this paper proposes a measurement circuit to extract the transient voltage of the power modules. This circuit can ease the difficulties of voltage change rate implementation in a power converter to support online health monitoring.

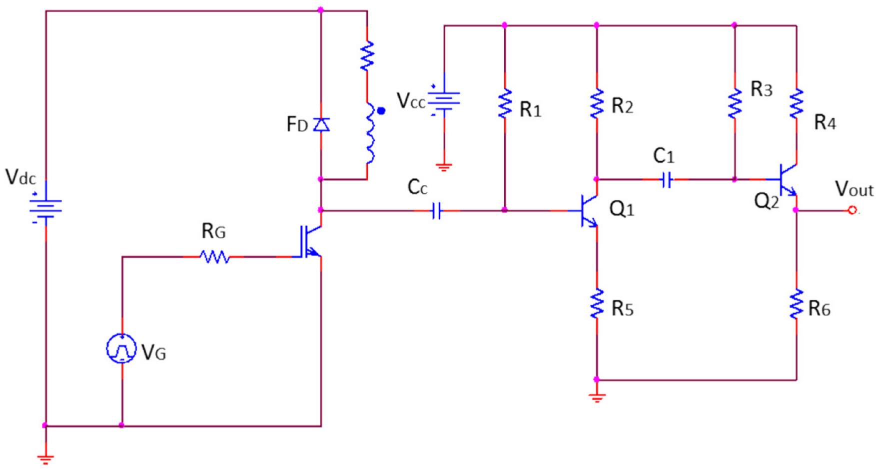

Fig. 2. Voltage change rate measurement circuit.

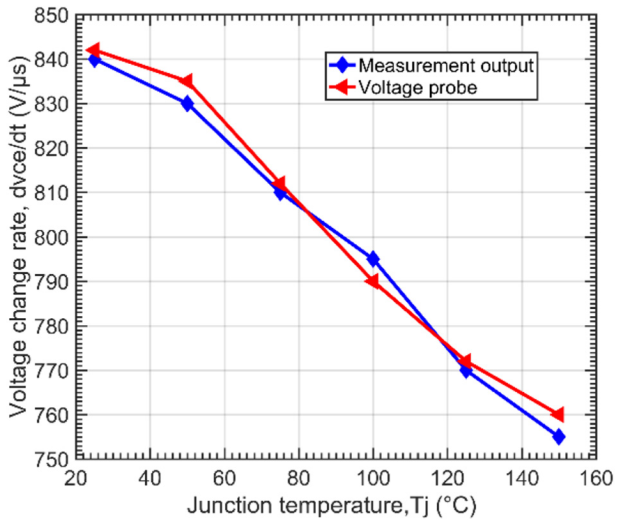

Fig. 3. Voltage change rate output.

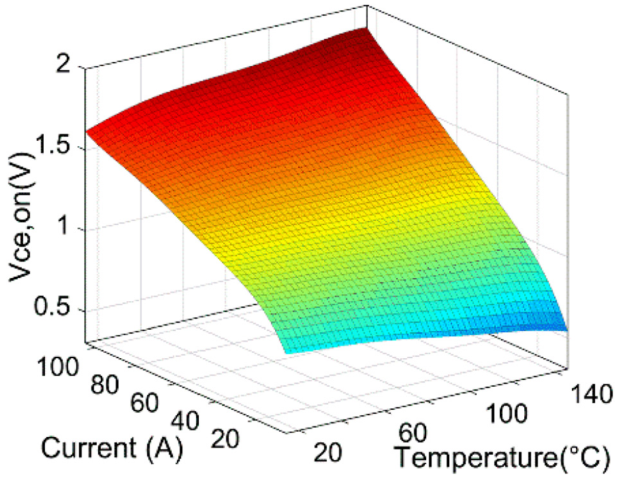

Fig. 4. Lookup table used to get junction temperature using $V_{ce,on}$ and i_c measurement.

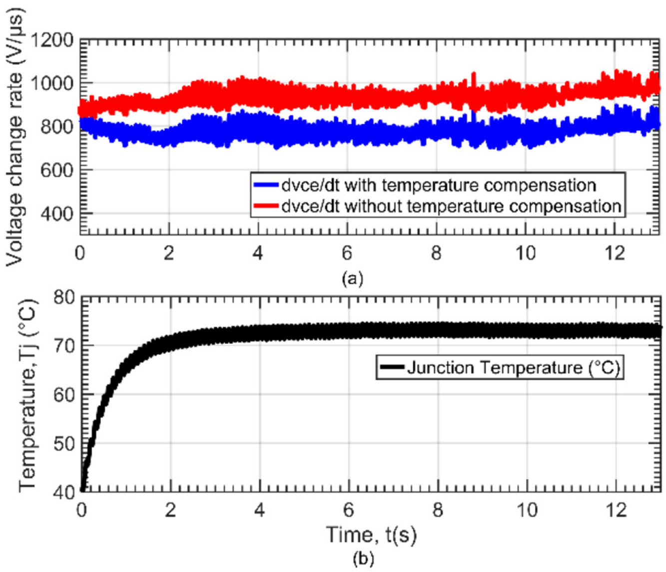

Fig. 5. (a) IGBT voltage change rate with and without considering junction temperature (T_j) (b) Corresponding junction temperature (Tj).

A typical test circuit that can be used to measure a voltage change rate is shown in Fig. 2. The voltage change rate is measured by using an external collector capacitor (C_C) connected in series with the collector terminal of the IGBT. It is important that the value of the external capacitor be less than that of the device collector-to-emitter capacitance and it is proposed to be 5% of the total collector capacitance of the device. Hence, the additional parasitic capacitance in the circuit will not affect the device performance significantly. The collector-emitter capacitance of the chosen module is 580 pF (SKM150GB12T4). Therefore, the external collector capacitor should be less than 10 pF. A 2 pF capacitor has been chosen to conduct the experiments.

Fig. 3 shows the comparison of voltage change rate measurement from the proposed measurement circuit and a high bandwidth differential probe. As seen, the maximum error between the measured and the extracted voltage change rate using the proposed sensing unit is less than 1%. From the result, it can also be observed that the voltage change rate has negative temperature coefficient with respect to junction temperature. Next step is to determine the junction temperature (T_j) of the device. Normally, the junction temperature of a power semiconductor device is not directly accessible. Hence, this work uses the device on-state voltage as a temperature sensitive parameter approach to extract the junction temperature of power module. Fig. 4 shows the lookup table used to obtain the junction temperature of IGBT device using current and voltage information from the online measurement. Initially, a curve tracer has been used to form a look-up table of the IGBT device at multiple temperatures. It has been reported that

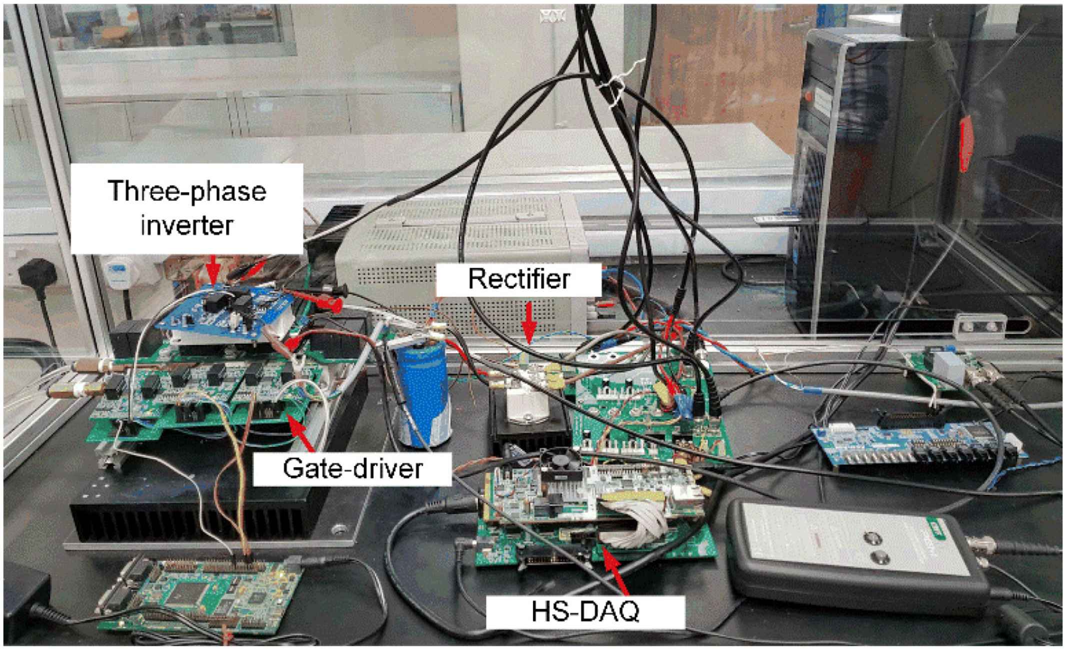

Fig. 6. Three-Phase inverter test-setup.

Table 1
Test rig parameters.

Parameter	Value
DC link voltage	150 V
Fundamental frequency	50 Hz
Switching frequency	2.5 kHz
Modulation index	0.8
DC link capacitor	3300 μF

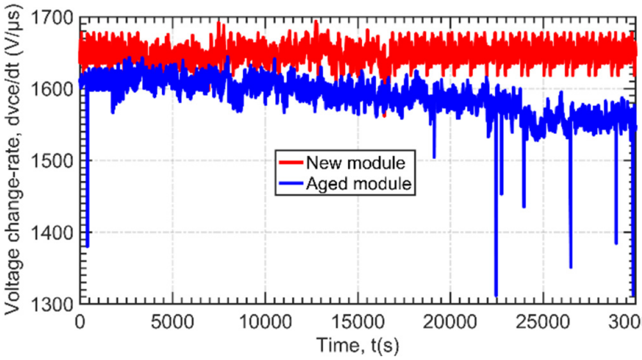

Fig. 7. Voltage change rate monitoring for new and aged power module of inverter system with $T_j = 40^{\circ}\mathrm{C}$ (SKM 150GB12T4).

temperature sensitive parameters were influenced by ageing [16]. Therefore, in this paper a separate look-up table has been formed to extract the junction temperature of the aged IGBT modules to avoid the influence of ageing in the electro-thermal sensitive parameter.

Fig. 5 shows the effect of junction temperature in IGBT voltage change rate under constant current (30A) and constant junction temperature ($T_j = 90\,^{\circ}\mathrm{C}$) condition with the applied DC link voltage of 100 V, as it can be seen from the experimental result, approximately 50-100 V/μs difference is captured between two estimated voltage change rates. Therefore, it is important to normalize the parameter based on operating conditions before using it as a precursor to identify the failure of the device.

Fig. 6 shows a three-phase inverter test rig which is built using three IGBT devices used in this experiment. To validate the proposed method, one IGBT module is partially aged till 10,000 cycles through an accelerated ageing test. Table 1 lists the specifications of the experimental test rig. In this test, the power device was loaded with the constant current profile with a maximum load current of 30 A and a switching frequency of 2.5 kHz. A high-speed data acquisition (HS-DAQ) is used to capture the data from the online monitoring circuit. Concurrently, a temperature estimation model implemented in a digital signal controller system captures the device operating conditions and estimates the device junction temperature.

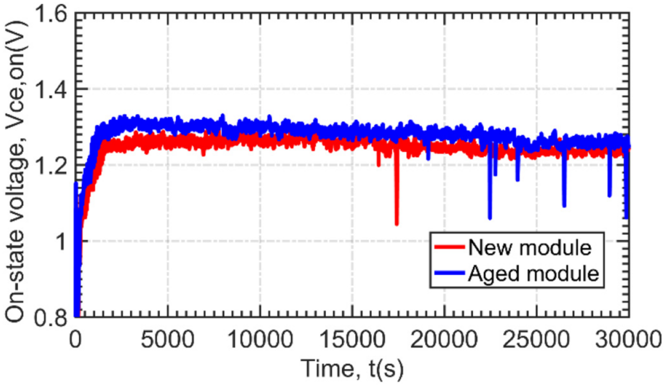

Fig. 8. On-state voltage change rate monitoring for new and aged power module of inverter system with $T_j = 40^{\circ}\mathrm{C}$ (SKM 150GB12T4).

The captured voltage change rate data from the HS-DAQ is normalized based on junction temperature and operating conditions. Both the parameters (voltage change rate and the on-state voltage) are affected by some signal drifts and noise during the online measurement, especially when the data is captured for a long time interval. However, the signal drift and noise interval are of very short duration, it can be minimized by optimizing the digital filter coefficients, and also by proper shielding of the HSDAQ system.

Fig. 7 shows the result of voltage change rate for a new and an aged power module of an inverter system under a constant load current of 30 A and a junction temperature of 40 °C. The experimental result shows that the aged module exhibits a lesser voltage change rate as

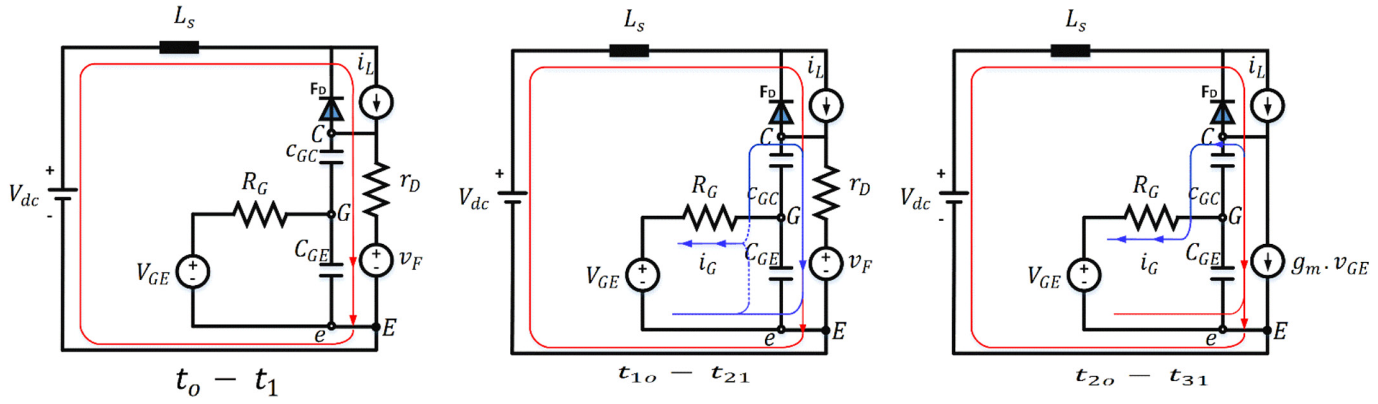

Fig. 9. IGBT turn off equivalent circuit with current paths during the switching interval.

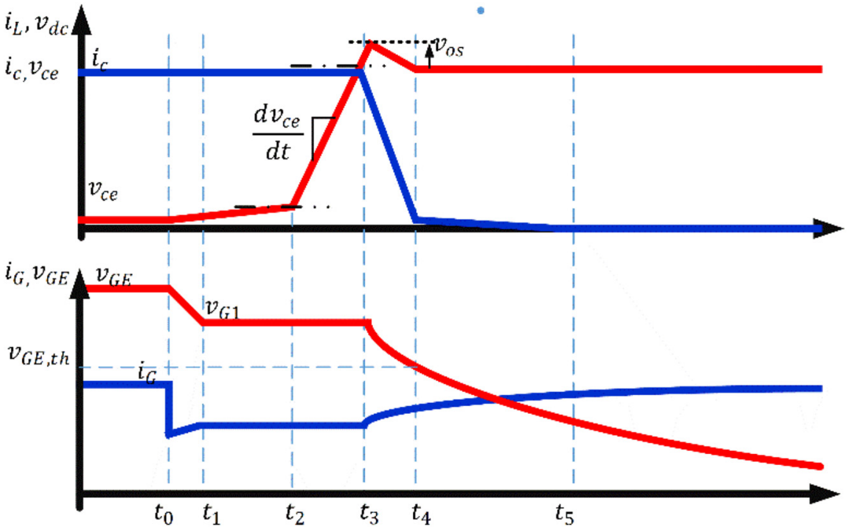

Fig. 10. IGBT turn-off switching characteristic.

ageing-progress. In the end, it is observed that the voltage change rate of the aged module is decreased approximately by 5% compared to the new power module. In addition to the voltage change rate, the device's on-state voltage was also monitored simultaneously as shown in Fig. 8. From the result, we can observe that the on-state voltage of the aged IGBT module shows signs of degradation. However, it varies less than +0.5%, whereas the voltage change rate decreases approximately +5%. This proves that the proposed precursor parameter is better at describing an early sign of device degradation compared to the well-known monitoring techniques based on on-state voltage.

4. Detailed analysis

From the experiments, it has been confirmed that the proposed precursor (voltage change rate) parameter captures the degradation of the aged device successfully. It is believed that this parameter change was caused by solder-die degradation, and it is due to permanent changes of the IGBT parasitic capacitances. However, there is no existing work in the technical literature proving that these precursor parameter changes were due to permanent changes in the IGBT parasitic capacitances. Therefore, this section examines the influence of ageing in parasitic capacitances and its relation to the proposed precursor parameter.

Fig. 9 shows the influence of gate- collector (CGC) capacitances during turn-off switching processes. Fig. 10 shows the typical switching behaviour of an IGBT during the turn-off period. During the interval $t_0 - t_1$:the IGBT gate input capacitance is discharged and the gate voltage falls from v_{GE} to v_{G1} with a time constant of $\tau_{G,\,1}$. The parallel combination of C_{GC} and C_{GE} is due to miller effect. The gate voltage and gate current during that period is given by,

$$v_{GE}(t) = v_{GE} - \Delta v_G.\left(1 - e^{-\frac{(t_0 - t_1)}{\tau_{G,1}}}\right) \tag{1}$$

$$i_G(t) = \frac{-\Delta v_G}{R_G}.\, e^{-\frac{(t_0 - t_1)}{\tau_G}} \tag{2}$$

During the interval $t_1 - t_2$: The gate voltage remains constant at v_{G1}, and the miller capacitances can be approximated as C_{GC}. During this period the collector-emitter voltage steeply increases with a time constant of R_G. C_{GC}.

$$\frac{dv_{CE}}{dt} = \frac{v_{G1}}{C_{GC}R_G} = -\frac{i_G}{C_{GC}} \tag{3}$$

From the switching interval $t_1 - t_2$ it is evident that the voltage-change rate is a function of gate-collector capacitance, and gate current of the device. It has been reported in [8] that the gate-current (i_G) of the IGBT decreases after chip failure.

However, the percentage of change is very small. Hence, the impact of gate-current (i_G) on the current change rate variation is assumed to be constant. Therefore, as suggested earlier, voltage change rate variation is due to permanent changes in parasitic capacitances. However, there are no existing studies looking into such a relationship. Therefore, accelerated ageing tests were conducted to investigate the variation of IGBT gate-collector capacitance (C_{GC}) with respect to chip solder

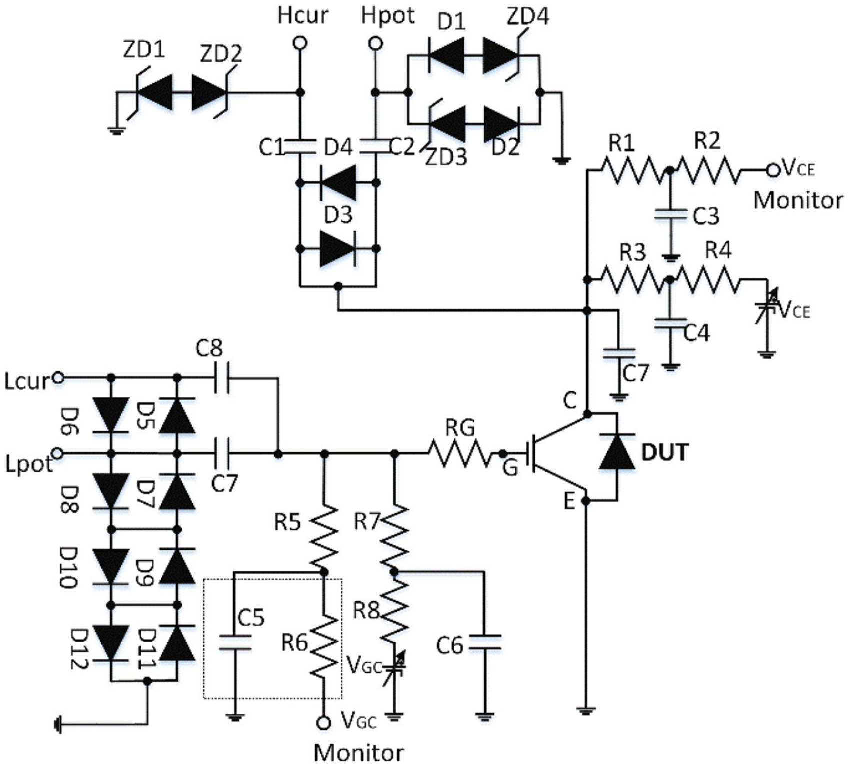

Fig. 11. IGBT Gate-collector capacitance C_{GC} measurement circuit.

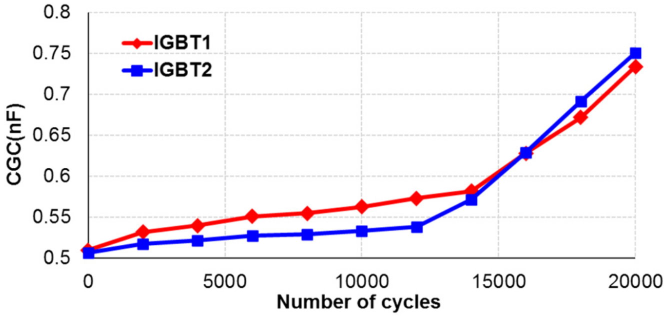

Fig. 12. Gate-collector capacitance variation with respect to thermal cycles.

fatigue and failures.

Fig. 11 shows the IGBT Gate-collector capacitance C_{GC} measurement circuit proposed by Tsuyoshi Funaki et al. [17]. This experiment is a four-terminal (H_{pot}, H_{cur}, L_{pot}, L_{cur}) kelvin-sense measurement connected to an LCR meter. Where, H_{pot} and L_{pot} is used to detect the ac voltage measurement signal, and H_{cur} and L_{cur} is used to detect the current measurement signal. Capacitors C1, C2, C3 and C4 blocks the dc bias voltage of V_{CE} and V_{GE}, the dc bias voltage is monitored through the RC filter. The blocked ac measurement signal is transferred to H_{cur} and H_{pot} terminals, L_{cur} and L_{pot} terminals, respectively. These blocking capacitor enables measurement of gate-collector capacitance characteristics related to the channel condition of an IGBT device. In this experiment, the bias voltage of V_{CE} is kept at $25V_{DC}$, and the frequency of the ac signal for capacitance measurement is kept at 1 MHz.

Fig. 12 presents the gate-collector capacitance (C_{GC}) of the IGBT at different ageing intervals. The capacitance measured under ambient temperature condition (25 °C) with applied bias voltage of $V_{CE} = 25$ V and V_{GE} kept at 0 V. As seen, there is no significant change in the gate-collector capacitance up to 5000 cycles. However, after 12,000 cycles, the gate-collector capacitance (C_{GC}) of the IGBTs starts to increase, and at 20,000 cycles capacitance reaches 0.74 nF, corresponding to 148% of its initial value. From the experiment, it has been concluded that the ageing leads to changes in the gate-collector capacitance. However, to confirm the physical changes (wear-out failure) in the power module. IGBT die was captured between the accelerated ageing tests using microscope.

Fig. 13. Microscopic image of an IGBT module.

Fig. 13 shows the microscopic image of a degraded IGBT. As seen, the fatigue appears on the corner of die attach areas, and spread towards the middle of the soldered materials with tiny cracks spotted in the corners of the bond wire and one bond wire lifted off as shown in

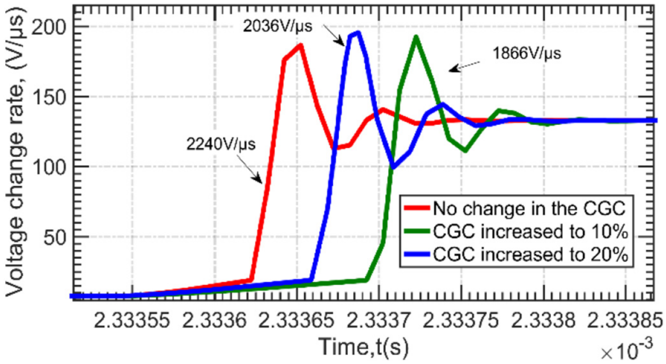

Fig. 14. Voltage change rate $\left(\frac{dv_{CE}}{dt}\right)$variation with respect to gate-collector capacitance (C_{GC}).

Table 2
Simulation setting parameters.

Parameter	Value
DC link voltage	140 V
Fundamental frequency	50 Hz
Switching frequency	2.5 kHz
Load	120 μH
DC link capacitor	3300 μF

the Fig. 13. This claim is also supported by Ginart et al. [18], where they specified that the permanent changes of the transistor parasitic elements is due to damage of the die or chip layer. Therefore, investigation concludes that the gate-collector capacitance variation is a sign of an IGBT wear-out failure. Specifically, it is the reflection of chip solder degradation and failure. Therefore, from the ageing test, it is evident that device ageing leads to changes in gate-collector capacitance, which decreases the voltage change rate of an IGBT module.

To verify this proposition, an IGBT simulation model has been developed in PSPICE platform, where the IGBT gate-collector have been varied from 5% to 10% of its initial value and the respective changes in the voltage-change rate have been presented in Fig. 14. The general setting parameter of this simulation test is listed in Table 2. Initially, under the normal operating condition, the voltage change rate was around 2240 V/μs and it drops to 2036 V/μs, when the gate-collector capacitance of the IGBT model was increased to 10%. It is further reduced to 1866 V/μs, when the gate-collector capacitance is increased by 20%. Therefore, from the simulation analysis, it has been concluded that the voltage change rate variation was due to changes in the IGBT collector capacitance.

5. Conclusion

This paper presented a new health monitoring precursor parameter, voltage change rate $\left(\frac{dv_{ce}}{dt}\right)$ to identify early degradation and failure of IGBT modules. The proposed parameter is investigated using accelerated ageing tests and from the results, one can conclude that, as the degradation of the IGBT module progresses, the voltage change rate decreases. The effectiveness of the proposed failure precursor parameter was proven with experiments conducted on the standalone IGBT modules using a three-phase inverter system under real-time operating conditions. From the experimental studies, it has been confirmed that the proposed precursor parameter captures the degradation of an aged module successfully. The voltage change rate parameter variation is due to the permanent change in the parasitic capacitance, and it is a sign of IGBT wear-out failure or early ageing of an IGBT, in particularly chip solder degradation and failure. To verify this proposition, the influence of ageing on the parasitic capacitance (gate-collector capacitance) is explored. Experimental investigation confirms that ageing leads to changes in gate-collector capacitance, which decreases the voltage change rate of an IGBT module. To prove the relation between voltage change rate and gate-collector capacitance, a simulation study has been conducted in PSPICE platform, where gate-collector capacitance has been adjusted to 5%, 10% of the initial value, and the subsequent voltage change rate is captured. The result from the simulation study also supported that the variation in the voltage change rate was specifically due to permanent changes in the gate-collector capacitance of an IGBT module. Therefore, compared to the conventional indicator, such as on-state voltage, the proposed indicator is more sensitive and can be used to identify the ageing as well as the incipient failures in IGBT modules.

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